Compressive-stress-induced T_c increase of the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phase

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The effect of compressive stress on T_c is studied for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phase. Although stress decreases the T_c of the high-T_c sample, the small compressive stress increases the T_c of the low-T_c phase. The maximum T_c^{off} is about 113.6 K at 0.01 mA/mm^2 (current density) and 3.92 N/mm^2 of the low-T_c phase where T_c^{off} is 96.2 K before loading. The maximum T_c^{off} is larger than the unloaded value (109.3 K) of the high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ sample. Based on the results of x-ray-diffraction, electrical-resistivity, and Seebeck-effect measurements, the T_c is dominated by carrier concentration and crystal perfection of the lattice ordering.

I. INTRODUCTION

From an engineering point of view, it is important to know the effect of compressive stress on T_c. Effects of compressive stress on T_c have been reported for $YBa_2Cu_3O_{7-y}$.[1,2] Although the compressive stress increased T_c^{on} and T_c^{mid}, the remarkable T_c^{off} increase with pressure had never been reported. However, we have recently found the small compressive-stress-induced T_c^{off} to increase for $YBa_2Cu_3O_{7-y}$.[3,4] Thus, we undertake to obtain information of the influence of the stress on T_c for the low- ($T_c=96$ K) and high- ($T_c=109$ K) T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples.

II. EXPERIMENTAL PROCEDURE

Samples with nominal composition were prepared by high-purity powders of CuO (99.9 mass%), PbO (99.9 mass%), $SrCO_3$ (99.9 mass%), $CaCO_3$ (99.9 mass%), and Bi_2O_3 (99.99 mass%). The powders were mixed and sintered in air at 1023 K for 8 h and then air cooled. After crushing, the sintered powders were resintered in air at 1073 K for 18 h and then air cooled. After crushing, a pellet-shaped tablet, 2 mm thick and 13 mm in diameter, was sintered in air at 1123 K for 12 h (low-T_c sample) and 75 h (high-T_c sample) and then furnace cooled.

The compressive stress was provided by a mechanical tester.[4] The electrical resistivity (Refs. 4 and 5) and Seebeck effect (Refs. 6 and 7) were measured in the tester. The stress was loaded by the stainless-steel rod attached to the specimen on the copper block. The electrical resistivity was measured using a standard four-probe technique and a Keithley 181 nanovoltmeter. The temperature was measured by an Au-Fe-chromel thermocouple attached to the specimen in a cryostat at equilibrium temperatures.[4] The structure of the samples was tetragonal.[5]

III. RESULTS AND DISCUSSION

A. T_c measurement

Figure 1 shows the temperature dependence of electrical resistivity (R) of the unloaded and loaded (3.92 N/mm^2) $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$. The lower the temperature, the lower the electrical resistivity becomes. Offset T_c^{off} and onset T_c^{on} of the transition are defined as the temperatures corresponding to the achievement of zero resistivity (below 10^{-9} Ω m at 1 mA/mm^2 of the current density) and to the deviation of the electrical resistivity. The deviated point is taken at $d(R/R_{300\,K})/dT=0.004$, where $d(R/R_{300\,K})/dT$ and $R_{300\,K}$ are the slope of the reduced electrical resistivity ($R/R_{300\,K}$) against the temperature graph and the resistivity at 300 K, respectively. The midpoint is designated as T_c^{mid}.

Figures 2 and 3 show changes in T_c^{off}, T_c^{mid}, and T_c^{on} with compressive stress. The solid and dashed lines are for the low- and high-T_c samples, respectively. The small stress enhances T_c^{off}, T_c^{mid}, and T_c^{on} of the low-T_c phase (solid lines), although the values decrease in the high-T_c sample (dashed lines). The slope of T_c^{on} is larger than that of T_c^{off} below the maximum value of the solid lines; T_c decreases above the maximum value. The maximum values of T_c^{off}, T_c^{mid}, and T_c^{on} are found at 3.92 N/mm^2 (solid lines). The maximum T_c^{off} is about 113.6 K at 0.01 mA/mm^2 of the current density for the low-T_c phase which T_c^{off} is 96.2 K before the loading. The maximum value is larger than the unloaded value (109.3 K) of the high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ sample.

B. X-ray diffraction

Figure 4 shows x-ray-diffraction peaks of the (002) plane for the low- and high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples. The low-T_c (96.2 K) sample shows at 5.9° of the (002) peak angle and shows that the double CuO layer appears.[8] On the other hand, the high-T_c sample has two (002) peaks at 5.9° and 4.8° (Ref. 9). The high-T_c phase (above 100 K) often has the triple CuO layer, which peak is found at 4.8°. Thus, the high-T_c sample is a mixture of the high-T_c and low-T_c phases.

Figures 5 and 6 show the changes in the lattice constant (c) and full width at half maximum intensity (FWHM) against the compressive stress of the unloaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples after the loading. The solid line is for the low-T_c phase. The dashed lines are

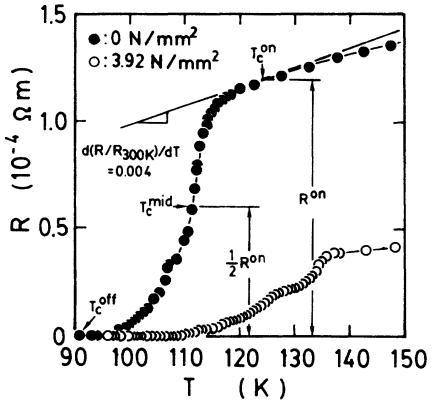

FIG. 1. Changes in electrical resistivity (R) vs temperature (T) for unloaded (●) and loaded (3.92 N/mm^2) (○) $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$.

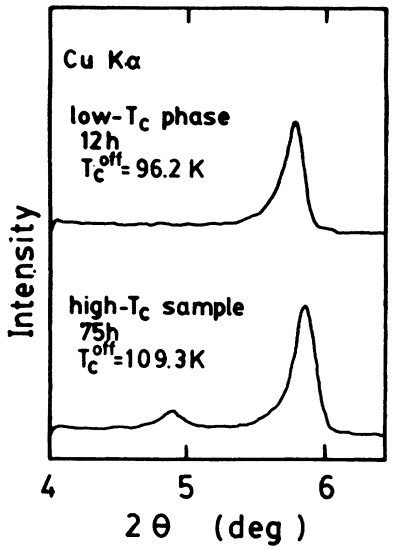

FIG. 4. X-ray diffraction pattern of the (002) plane for low- and high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples.

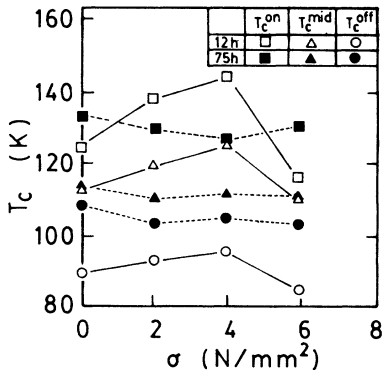

FIG. 2. Changes in the superconducting transition temperature (T_c) with compressive stress (σ) for the $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases at 1 mA/mm^2 of current density.

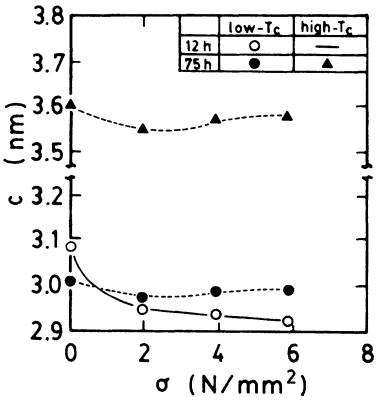

FIG. 5. Changes in the lattice constant (c) against compressive stress (σ) of unloaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples after loading.

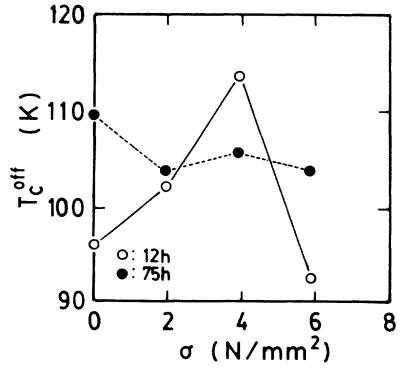

FIG. 3. Changes in the offset temperature (T_c^{off}) of the superconducting transition temperature with compressive stress (σ) at 0.01 mA/mm^2 of current density for the $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases.

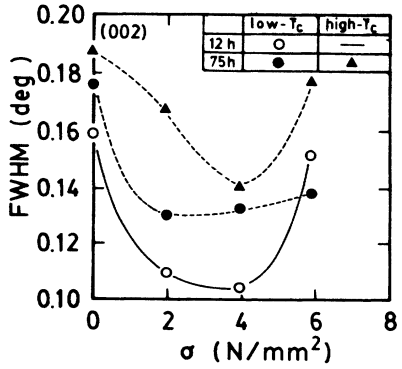

FIG. 6. Changes in FWHM against the compressive stress (σ) of unloaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples after loading.

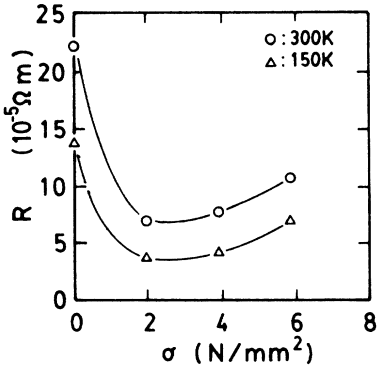

FIG. 7. Changes in electrical resistivity (R) against compressive stress (σ) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases.

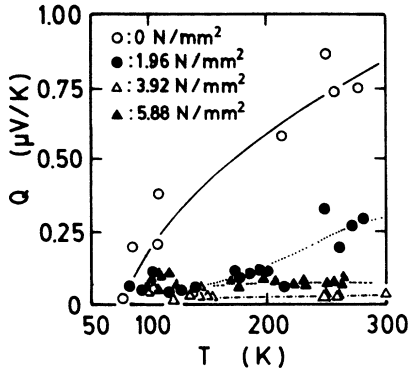

FIG. 9. Changes in the Seebeck coefficient (Q) against temperature (T) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases (loaded and unloaded).

for the high-T_c sample. The small load decreases the lattice constant for 1.96 N/mm^2 of the unloaded sample after the loading (see Fig. 5). The small load decreases FWHM for 3.92 N/mm^2 (see Fig. 6). FWHM is the width of the x-ray-diffraction peaks at half height. Thus, the small compressive stress enhances the crystal perfection of the lattice ordering. These results mean that the small stress easily moves the atoms distributed in expansive (uncompressive) sites, whereas the stress does not easily move the atoms in the compressive sites. Namely, the stress decreases the lattice constant and FWHM. The smaller the FWHM, the higher the degree of the crystal-lattice ordering becomes, resulting in high T_c by the small amount of the stress in the low-T_c phase.

The excess stress increases FWHM and slightly decreases the lattice constant. They show that the large stress moves the atoms in the compressive stress and disorders the crystal-lattice ordering. Although the similar changes in c and FWHM are found for the high-T_c samples (dashed lines in Fig. 6), the T_c increase has never been observed. The slight increases in the lattice constants are found above the minimum point (see dashed lines in Fig. 5). It shows that some disaccommodations (such as microcracks) exist. If the more careful treatment is performed without any disaccommodation, the stress-induced T_c increase will probably be found in the high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ samples.

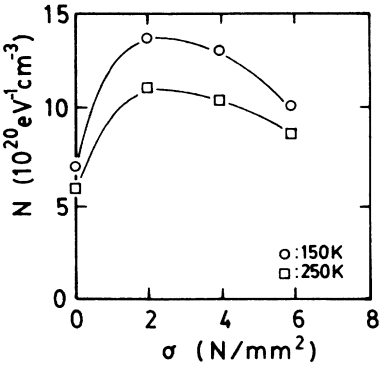

FIG. 8. Changes in density of state (N) against compressive stress (σ) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases.

C. Electronic discussion

Carrier concentration (c^*) is one of the dominant factors that control the T_c. The Seebeck constant (Q) is expressed by the following.[6,7]

$$Q = \pm(k/e)[\ln(N/c^*) + A] . \quad (1)$$

Here, k, e, and N are the Boltzmann constant, electron charge, and density of state, respectively; A is a constant. Thus, c^* is expressed by the following:

$$c^* = N/\exp[(\pm eQ/k) - A] . \quad (2)$$

To obtain c^*, the density of state (N) is calculated by the use of the electrical resistivity (R_e). N is expressed by the following:[10]

$$N = A'/R_e^{1/2} . \quad (3)$$

Here, A' is a constant that is dominated by the electron mass, charge, Planck constant, and mean free path. If the stress does not largely change their values, the N value is inversely proportional to the $R_e^{1/2}$ value.

Figure 7 shows the change in the electrical resistivity against the stress. The small compressive stress decreases the resistivity and increases the density (see Fig. 8). Here,

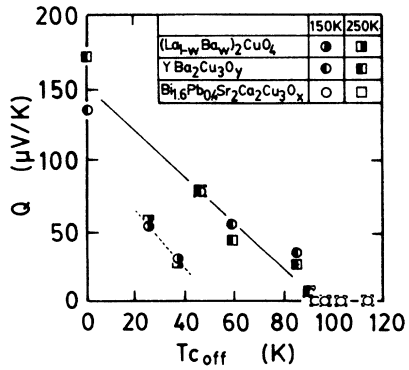

FIG. 10. Changes in the Seebeck coefficient (Q) against the offset temperature (T_c^{off}) of the superconducting transition for $(La_{1-w}Ba_w)_2CuO_4$ (Refs. 12 and 13) and YBa_2Cu_3Oy (Refs. 13 and 14), together with the unloaded and loaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases (see Fig. 9).

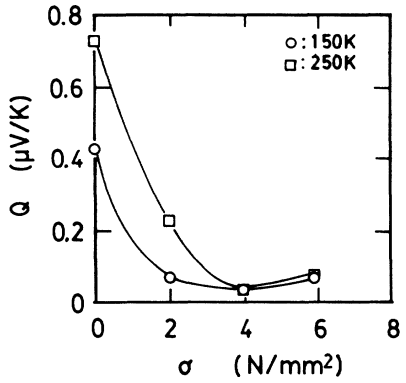

FIG. 11. Changes in the Seebeck coefficient (Q) against compressive stress (σ) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases.

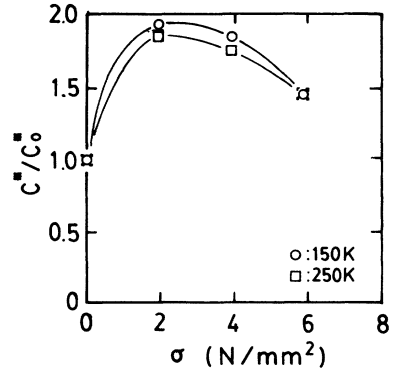

FIG. 12. Changes in reduced carrier concentration (C^*/C_0^*) against compressive stress (σ) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases. C^* is the carrier concentration at different loads. C_0^* is for the unloaded sample.

the electron mean free path is assumed to be constant and to be equal to the lattice constant of the c axis. Namely, the larger the stress, the higher the density of state becomes, resulting in high T_c. On the other hand, since the excess stress slightly decreases the density, it decreases the T_c.

Figure 9 shows the temperature dependence of the Seebeck coefficient (Q) for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases that are loaded and unloaded. As compared with the unloaded sample, the loaded samples under the small stress show the temperature-independent Seebeck coefficient. The temperature-independent Q is considered to be strongly correlated with the electron system.[11,12] If the correlation among electrons is very strong, the Mott-Hubbard band must be formed and the half-filled conduction band is split into two bands.

Based on Eq. (2), the smaller the Q, the higher the carrier concentration (c^*) becomes. Figure 10 shows the relationship between Q (Ref. 13) and T_c^{off} (Refs. 12 and 14) for $YBa_2Cu_3O_{7-y}$ and $(La_{1-w}Ba_w)_2CuO_4$, together with the loaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases. The lower the Q, the higher the T_c^{off} becomes for the high-T_c oxides. The $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases show the small Q. Figure 11 shows change in the Q against the compressive stress. The small stress decreases Q rapidly. The excess stress slightly increases Q. Thus, the Q change in Fig. 11 coincides with the T_c change in Figs. 2 and 3.

Since the small stress decreases Q and increases N, the large value of c^* is obtained by the small compressive stress by use of Eq. (2). Figure 12 shows the c^* change against the compressive stress. The c^* change approximately agrees with the T_c change (see Figs. 2 and 3). Namely, the higher the carrier concentration, the higher the T_c becomes for the loaded $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phases.

Since the band gaps for the high-T_c oxides are smaller than those of the semiconductors, A is about zero. Furthermore, the high-T_c oxides show small Q. The exponential term in Eq. (2) is about 1. Thus, we suggest that c^* is mainly dominated by the density of state (N) for the high-T_c oxides.

IV. CONCLUSION

The effect of compressive stress on T_c is studied for the low-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ phase. Although the stress decreases T_c of the high-T_c sample, the small compressive stress increases T_c of the low-T_c phase. The maximum T_c^{off} is about 113.6 K at 3.92 N/mm^2 of the low-T_c phase ($T_c^{\text{off}}=96.2$ K before the loading). It is larger than the unloaded value (109.3 K) of the high-T_c $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_x$ sample. Based on the results of the x-ray diffraction, electrical resistivity, and Seebeck effect, we conclude that the high carrier concentration and the crystal perfection of the lattice ordering enhance the T_c value.

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